Factors Influencing Occurrence, Scale, Mobility, Runout, and Morphology of Mass Movements on the Continental Slope

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LONG-TERM GOAL

Achieve an improved understanding of the relationships between sedimentation, environment, and the morphology of continental slopes. This goal will be accomplished primarily through investigations within the northern California (Eel River) study area and incorporation of data from around the World. An underlying assumption of our work is that the occurrence and morphology of mass movement features on the continental slope depend upon a combination of characteristics, each of which varies over the region in a consistent manner. The various components of this project are part of a concerted effort between the geotechnical groups at the USGS and Laval University. Their activities are very much interwoven but, for administrative reasons, their respective budgets are identified separately as are the annual reports.

OBJECTIVES

Identify factors that can be mapped regionally and that determine where and how slope failures occur; derive a basis for producing regional maps that indicate relative landslide susceptibility. Model shear strength development with depth and incorporate this model into continental slope stability, post-failure behavior, and bedform processes. Observe and model pore pressure development in continental slopes. Analyze the relationship between seismic intensity, sediment instability and slope processes. Integrate these elements into geo-hazards assessment.

APPROACH

Our research focuses on the factors that lead to variations in the sedimentological and environmental conditions determining slope failure. We develop improved correlations between engineering classifications and strength factors. We measure excess pore water pressures in situ. We simulate sediment accumulation in specially designed cells. Geotechnical properties are related to sediment density state, obtained from detailed logs of downcore variability of sediment density and sound velocity. Using available bathymetry, we construct slope maps. Seismic shaking variations are evaluated probabilistically by seismologists. In situ pore pressures are determined by means of the Excalibur probe (AGC-Atlantic). These pressures can be generated if the sedimentation rate is particularly rapid, if there is charging by bubble-phase gas, or if earthquake shaking disrupts the sediment fabric and causes it to collapse with a resulting increase in the pressure of interstitial fluids.

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14. ABSTRACT
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Driving stresses are balanced against strength in a geographic Information System (GIS) to obtain a regional estimate of relative slope stability.

Key individuals, at USGS: Homa Lee, Kevin Orzech, Diane Minasian, Peter Dartnell, and Florence Wong: physical property logs of sediment cores and relations between geotechnical and classification properties, algorithms relating sediment properties, environmental factors, and slope stability within the framework of a GIS; at Laval: Jacques Locat, Jean-Marie Konrad, Serge Leroueil, and Priscilla Desgagnész: strength and compressibility measurements, SEM studies, and rheology measurements, and simulation of sediment accumulation.

WORK COMPLETED

In FY01, we continued our development of a GIS-based approach toward a geo-hazards assessment of offshore landslides. We have produced maps, based on sediment distribution, slope steepness, and anticipated seismic shaking, that show predicted measures of slope stability for the Eel and Los Angeles margins (Fig. 1). Papers presenting our methodology were presented at the International Symposium on Landslides in Cardiff, Wales and at the European Union of Geosciences meeting in Strasbourg, France. We are also developing a more fundamental relationship between landslide occurrence and sediment lithology. In the past we have relied upon surficial sediment density as a measure of lithology. We are expanding our correlations to include engineering classifications that are not impacted by consolidation state.

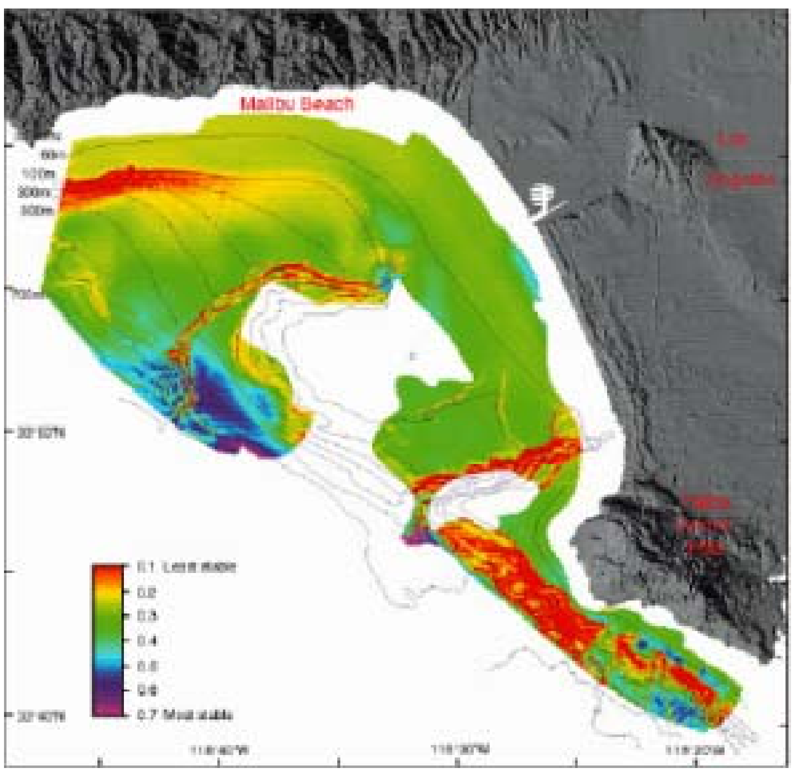

Figure 1. Prediction of relative slope stability for the Los Angeles margin based on a GIS analysis of slope steepness, anticipated seismic shaking, and sediment characteristics. Warmer colors correspond to greater likelihood of slope failure.

We are continuing to test cores taken on the New Jersey Margin area from the Marion Dufresne cruise. A total of 3 long cores were collected (MD9922-11, 12, and 13), of which one is kept at Laval and is being shared with the USGS group for various geotechnical tests. All cores were logged, onboard the ship, at 1-cm resolution for density, sound velocity, and magnetic susceptibility. We are also using a laboratory simulation to determine how significant repeated seismic shaking is gradually increasing the strength of marine sediment on slopes.

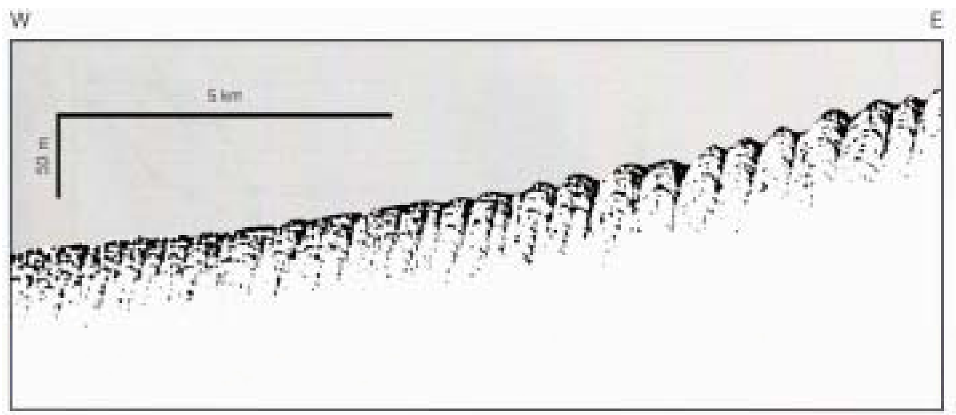

Figure 2. A feature on Monterey Fan that is generally accepted as a field of migrating sediment waves.

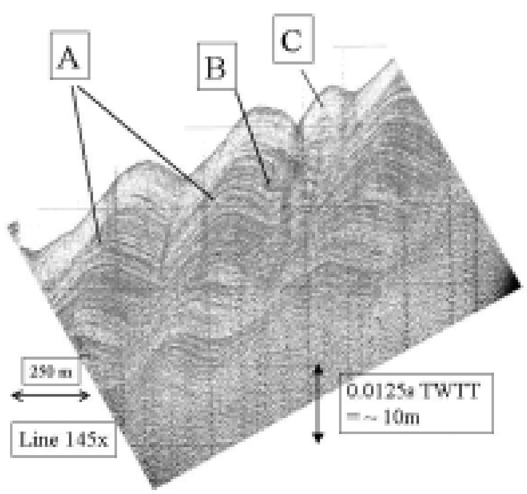

Figure 3. Part of a feature on the Eel Margin that has previously been interpreted as a submarine landslide but that contains many characteristics suggestive of a field of migrating sediment waves.

We are collaborating with Syvitski, Parker, Orange, Locat in recognizing and interpreting migrating sediment waves. We feel that these features are common along continental margins and that they are frequently misinterpreted as submarine landslides (Figures 2 and 3). We developed criteria for recognizing these features and applied numerical and physical models to understand the mechanics of their development. We prepared a paper for a special issue of Marine Geology that deals with migrating sediment waves. The paper includes empirical, theoretical, and laboratory results that show

the mechanism of formation of these features and illustrate the ways to distinguish these features from submarine slope failures.

RESULTS

Classic slope failure features on the Eel Margin are rare even though our methodology shows a high vulnerability to slope failure during seismic loading, indicating either that mass wasting on the Eel Margin takes unexpected forms or that mass wasting is less significant than would be expected. Shallow-seated failures are more common on the Los Angeles Margin. Our methodology shows even higher vulnerability to slope failure in Los Angeles Margin areas experiencing numerous shallow-seated failures. Our methodology shows promise in terms of delineating the environmental conditions that are conducive to shallow-seated submarine slope failure.

In collaboration with Laval, analyses of reconstituted specimens of Eel river sediment have been subjected to drained cyclic loading. Under conditions comparable to a series of earthquakes, we have found that the undrained shear strength increases significantly.

Examination of accepted sediment wave fields reveal nine diagnostic characteristics. When these characteristics are applied to other features previously attributed to submarine landslide deformation; they suggest a reinterpretation towards one of migrating sediment-wave fields. The reassessment suggests that numerous turbidity currents separated by intervals of ambient hemipelagic sedimentation deposited the wave fields over a long time (thousands of years). Numerical experiments demonstrate that if a series of turbidity currents flows across a rough seafloor, sediment waves form and migrate upslope. Hemipelagic sedimentation between turbidity current events facilitate the upslope migration of the sediment waves. Physical modeling of turbidity currents confirms the formation and migration of seafloor bedforms. The morphology of sediment waves generated both numerically and physically in the laboratory bears a strong resemblance to those observed in the field, including those that have previously been described as submarine landslides.

IMPACT/APPLICATION

Relationships developed in this project show the importance of sediment liquidity index and seabed density profiles in representing the behavior of marine sediment. These values can be used to predict regional slope stability and the rheological behavior of debris flows. This project shows the value of GIS techniques in combining the impact of a variety of marine sediment and environmental factors to yield information about a predicted outcome, in this case, susceptibility to slope failure. General strength-density relations can be used for modeling sediment accumulation and stability.

Reinterpretation of certain morphologic features as migrating sediment waves rather than submarine landslides has a significant impact on hazard assessment and models of continental slope deposition. Although both turbidity currents, which would need to be present to form sediment waves, and submarine landslides are hazards to offshore structures, they act differently on the structures and require different engineering considerations to mitigate their effect. Likewise, the presence of migrating sediment waves indicates the presence of turbidity currents or strong bottom currents, whereas submarine landslides can occur with sediment bodies deposited in a larger number of ways.

TRANSITIONS

Geoacoustic properties are being used by mappers and acousticians to identify lithologies acoustically. Rheological properties are being used by modelers to represent debris flows. Landslide generation models are being used by landscape evolution modelers.

RELATED PROJECTS

Lee has developed a USGS project to investigate sediment and pollutant transport on the Los Angeles margin using many of the same techniques produced by STRATAFORM. Locat is investigating the behavior of a newly formed sediment layer acting as a natural cap over contaminated sediment in Canada. Locat, Lee, and a group of Canadian scientists and engineers have developed a project (COSTA Canada) to collaborate with the European COSTA (COntinental Slope STAbility) project. This will allow us to verify in other environments many of the concepts developed with STRATAFORM support.

REFERENCES

Desgagnés, P., Locat, J., Lee, H.J., Leroueil, S., Alexander, C., Mountain, G., and Pratson, L., 2000. Geotechnical properties of a mass flow deposit on the Hudson Apron, off New Jersey, U.S.A.. Comptes rendus, 53e Conférence canadienne de géotechnique, Montréal, vol. 1: 137-144.

Desgagnés, P., Locat, J., Lee,. H., and Leroueil, S., 2001. Le glissement du Hudson Apron : un exemple d'application de la caractérisation géomécanique des mouvements de masse. Comptes rendus de la 54e Conférence canadienne de géotechnique, Calgary. In press.

Imran, J., Parker, G., Locat, J., and Lee, H., 2000. A 1-D numerical model on muddy subaqueous and subareial debris flows. Submitted to ASCE Journal of Hydraulic Engineering.

Lee, H.A., Locat, J., Dartnell, P., Israel, K., and Wong, F., 1999. Regional variability of slope stability: application to the Eel Margin, California. Marine Geology, 154: 305-322.

Lee, H.J., Locat, J., Dartnell, P., Minasian, D., and Wong, F., 2000. A GIS-based regional analysis of the potential for shallow-seated submarine slope failure. Proceedings, 8th International Symposium on Landslides, Cardiff, England, v. 2, p. 913-922.

Lee, H., Locat, J., Dartnell, P., Minasian, D., and Wong, F., 2001. Regional variability of factors that influence offshore slope stability, synthesis within a GIS. XI European Union of Geosciences meeting, Strasbourg, Session RCM4, p739.

Leroueil, S., Locat, J., Vaunat, J., Picarelli, L., and Lee, H., and Faure, R., 1996. Geotechnical characterization of slope movements. Keynote paper, 7th International Symposium on Landslides, Trondheim, Norway, . vol. 1, pp.: 53-74.

Locat, J., Desgagnés, P., Leroueil, S., Lee, H., and Héroux, M.-C., 2001. The geotechnical characterization of mass movements as o component of submarine landslides risk assessment : an application to the New Jersey Margin. XI European Union of Geosciences meeting, Strasbourg, Session RCM4, p. 735.

Locat, J., Lee, H., and Locat, P., 2000. Analysis of Submarine Mass Movements and its Implication for the Generation of Tsunamis, with a Particular Reference to the Palos Verdes Slide, California. In: Proceedings of the Workshop on the Prediction of Underwater Landslide and Slump Occurrence and Tsunami Hazards off Southern California, Los Angeles, March 10-11 2000, In Press.

Locat, J., and Lee, H.J., 2002. Submarine landslides : advances and challenges. Keynote presentation, 8th International Symposium on Landslides, Cardiff, U.K., June 2000. Canadian Geotechnical Journal, vol. 39, no. 2.

Locat, J., Mayer, L., Gardner, J., Lee, H., Kammerer, E., and Doucet, N., 1999. The use of multibeam surveys for submarine landslide investigations. Invited Article. International Symposium on: Slope Stability Engineering: Geotechnical and Geoenvironmental Aspects, Shikoku, Japan, 8 p., in press.

PUBLICATIONS

Goff, J.A., Wheatcroft, R.A., Lee, H.J., Drake, D.E.. Swift, D.J. P. and Fan, S., 2002. Spatial Variability of Shelf Sediments in the STRATAFORM Natural Laboratory, Northern California, Continental Shelf Research, submitted.

Lee, H.J., Syvitski, J.P.M., Parker, G., Orange, D., Locat, J., Hutton, E.W.H., and Imran, J., 2002, Turbidity-current generated sediment waves: modeling and field examples, Marine Geology, in press.

Lee, H.J., Syvitski, J.P.M., Parker, G., Orange, D., Locat, J., Hutton, E.W.H., and Imran, J., 2001, Distinguishing submarine landslide deposis from migrating sediment wave fields, Eos., in press.

Locat, J. Lee. H.J., Kayen, R., Israel, K., Savoie, M.-C., and BOULANGER, É., 2001. Shear strength development with burial in recent Eel River Margin slope sediments. Submitted to: Marine Geotechnology and Resources.

Urgeles, R., Locat, J., Lee, H. and Martin, F. 2001. The Saguenay Fjord, Québec, Canada: Integrating marine geotechnical and geophysical data for spatial seismic slope stability and hazard assessment. Accepted, Marine Geology, in press.